Charm System Tests of CPT and Lorentz Invariance with FOCUS

The FOCUS Collaboration[⋆]

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Abstract

We have performed a search for CPT violation in neutral charm meson oscillations. While flavor mixing in the charm sector is predicted to be small by the Standard Model, it is still possible to investigate CPT violation through a study of the proper time dependence of a CPT asymmetry in right-sign decay rates for $D^0 \to K^- \pi^+$ and $\overline{D}^0 \to K^+ \pi^-$. This asymmetry is related to the CPT violating complex parameter ξ and the mixing parameters x and y: $A_{CPT} \propto \operatorname{Re} \xi \, y - \operatorname{Im} \xi \, x$. Our 95% confidence level limit is $-0.0068 < \operatorname{Re} \xi \, y - \operatorname{Im} \xi \, x < 0.0234$. Within the framework of the Standard Model Extension incorporating general CPT violation, we also find 95% confidence level limits for the expressions involving coefficients of Lorentz violation of $(-2.8 < N(x,y,\delta)(\Delta a_0 + 0.6 \, \Delta a_Z) < 4.8) \times 10^{-16}$ GeV, $(-7.0 < N(x,y,\delta)\Delta a_X < 3.8) \times 10^{-16}$ GeV, and $(-7.0 < N(x,y,\delta)\Delta a_Y < 3.8) \times 10^{-16}$ GeV, where $N(x,y,\delta)$ is the factor which incorporates mixing parameters x, y and the doubly Cabibbo suppressed to Cabibbo favored relative strong phase δ.

1 Introduction

The combined symmetry of charge conjugation (C), parity (P), and time reversal (T) is believed to be respected by all local, point-like, Lorentz covariant field theories, such as the Standard Model. However, extensions to the Standard Model based on string theories do not necessarily require CPT invariance, and observable effects at low-energies may be within reach of experiments studying flavor oscillations [1,2]. A parametrization [3] in which CPT and T violating parameters appear has been developed which allows experimental investigation in many physical systems including atomic systems, Penning traps, and neutral meson systems [4]. Using this parameterization we present the first experimental results for CPT violation in the charm meson system.

Searches for CPT violation have been made in the neutral kaon system. Using an earlier CPT formalism [5,6], KTeV reported a bound on the CPT figure of merit $r_K \equiv |m_{K^0} - m_{\overline{K}^0}|/m_{K^0} < (4.5 \pm 3) \times 10^{-19}$ [7]. A more recent analysis, using framework [3] and more data extracted limits on the coefficients for Lorentz violation of $\Delta a_X, \Delta a_Y < 9.2 \times 10^{-22}$ GeV [8]. CPT tests in B^0 meson decay have been made by OPAL at LEP [9], and by Belle at KEK which has recently reported $r_B \equiv |m_{B^0} - m_{\overline{B}^0}|/m_{B^0} < 1.6 \times 10^{-14}$ [10].

To date, no experimental search for CPT violation has been made in the charm quark sector. This is due in part to the expected suppression of $D^0 - \overline{D}^0$ oscillations in the Standard Model, and the lack of a strong mixing signal in the experimental data. Recent mixing searches include a study of lifetime differences between charge-parity (CP) eigenstates [11,12,13], a study of the time evolution of D^0 decays by CLEO [14] and a study of the doubly Cabibbo suppressed ratio (R_{DCS}) for the decay $D^0 \rightarrow K^+\pi^-$ [15]. Even without knowledge of the mixing parameters, one can investigate CPT violation through a study of the time dependence of D^0 decays. The time evolution of neutral-meson state is governed by a 2×2 effective Hamiltonian Λ in the Schrödinger equation. Indirect CPT violation occurs if and only if the difference of diagonal elements of Λ is nonzero. The complex parameter ξ controls the CPT violation and is defined as $\xi = \Delta\Lambda/\Delta\lambda$, where $\Delta\Lambda = \Lambda_{11} - \Lambda_{22}$ and $\Delta\lambda$ is the difference in the eigenvalues. ξ is phenomenologically introduced and therefore independent of the model. Time dependent decay probabilities into right-sign ($D^0 \rightarrow K^-\pi^+$) and wrong-sign decay modes (wrong sign is used here in the context of decays via mixing, $D^0 \rightarrow \overline{D}^0 \rightarrow K^+\pi^-$) for neutral mesons which express the CPT violation have been developed in a general parametrization [3]. For the decay of a D^0 to a right-sign final state f, the time dependent decay probability is:

$$P_f(t) \equiv |\langle f|T|D^0(t)\rangle|^2 = \frac{1}{2}|F|^2 \exp(-\frac{\gamma}{2}t)$$
$$\times [(1 + |\xi|^2)\cosh\Delta\gamma t/2 + (1 - |\xi|^2)\cos\Delta mt$$
$$-2\text{Re}\,\xi\,\sinh\Delta\gamma t/2 - 2\text{Im}\,\xi\,\sin\Delta mt]. \tag{1}$$

The time dependent probability for the decay of a $\overline{D}^0$ to a final state $\overline{f}$, $\overline{P_{\overline{f}}}(t)$, may be obtained by making the substitutions $\xi \to -\xi$ and $F \to \overline{F}$ in the above equation. $F^* = \overline{F}$ is strictly true if CP (CPT) is not directly violated, which experimental evidence suggests is very nearly true in charm decays. $F = \langle f|T|D^0 \rangle$ represents the basic transition amplitude for the decay $D^0 \to f$, $\Delta\gamma$ and Δm are the differences in physical decay widths and masses for the propagating eigenstates and can be related to the usual mixing parameters [12] $x = \Delta M/\Gamma = -2\Delta m/\gamma$, $y = \Delta\Gamma/2\Gamma = \Delta\gamma/\gamma$, and γ is the sum of the physical decay widths. Expressions for wrong-sign decay probabilities involve both CPT and T violation parameters which only scale the probabilities, leaving the shape unchanged. Using only right-sign decay modes, and assuming neglible direct CPT violation, the following asymmetry can be formed,

$$A_{\text{CPT}}(t) = \frac{\overline{P_{\overline{f}}}(t) - P_f(t)}{\overline{P_{\overline{f}}}(t) + P_f(t)}, \tag{2}$$

which is sensitive to the CPT violating parameter ξ:

$$A_{\text{CPT}}(t) = \frac{2\text{Re}\,\xi\,\sinh\Delta\gamma t/2 + 2\text{Im}\,\xi\,\sin\Delta mt}{(1+|\xi|^2)\cosh\Delta\gamma t/2 + (1-|\xi|^2)\cos\Delta mt}. \tag{3}$$

Experiments show that x, y mixing values are small ($< 5\%$). Equation 3, for small x, y and t, reduces to:

$$A_{\text{CPT}}(t) = (\text{Re}\,\xi\,y - \text{Im}\,\xi\,x)\,\Gamma\,t. \tag{4}$$

2 Experimental and analysis details

In this paper we search for a CPT violating signal using data collected by the FOCUS Collaboration during an approximately twelve month time period in 1996 and 1997 at Fermilab. FOCUS is an upgraded version of the E687 spectrometer. Charm particles are produced by the interaction of high energy photons (average energy ≈ 180 GeV for triggered charm states) with a segmented BeO target. In the target region, charged particles are tracked by up to sixteen layers of microstrip detectors. These detectors provide excellent vertex resolution. Charged particles are further tracked by a system of five multi-wire proportional chambers and are momentum analyzed by two oppositely polarized large aperture dipole magnets. Particle identification is accomplished by three multi-cell threshold Čerenkov detectors [16], two electromagnetic calorimeters, an hadronic calorimeter and muon counters.

We analyze the two right-sign hadronic decays $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$. We use the soft pion from the decay $D^{*+} \to D^0\pi^+$ to tag the flavor of the D at production, and the kaon charge in the decay $D^0 \to K^-\pi^+$ to tag the D flavor

at decay. $D^0 \rightarrow K^-\pi^+$ events are selected by requiring a minimum detachment ℓ of the secondary (decay) vertex from the primary (production) vertex of $5\,\sigma_\ell$, where σ_ℓ is the calculated uncertainty of the detachment measurement. The primary vertex is found using a candidate driven vertex finder which nucleates tracks about a "seed" track constructed using the secondary vertex and the D momentum vector. Both primary and secondary vertices are required to have fit confidence levels greater than 1%. The D^*-tag is implemented by requiring the $D^* - D^0$ mass difference be within 3 MeV/c^2 of the nominal value [17]. A χ^2-like variable called $W_i \equiv -2\log(\text{likelihood})$, where i ranges over electron, pion, kaon and proton hypotheses is used for particle identification [16]. For the K and the π candidates we require W_i to be no more than four units greater than the smallest of the other three hypotheses ($W_i - W_{min} < 4$) which eliminates candidates that are likely to be mis-identified. In addition, D^0 daughters must satisfy the slightly stronger $K\pi$ separation criteria $W_\pi - W_K > 0.5$ for the K and $W_K - W_\pi > -2$ for the π. Events in which the final state $K^-\pi^+$ is identified as π^-K^+ and vice versa are removed by imposing a hard Čerenkov cut on the sum of the two separations (($W_\pi - W_K)_K + (W_K - W_\pi)_\pi > 8$). $K\pi$ pairs with highly asymmetrical momenta are more likely to be background than signal. A cut is made on the momentum asymmetry, $P_A = |(P_K - P_\pi)/(P_K + P_\pi)|$, to reject these candidates. The best background rejection is achieved by applying the cut in the following way, $P(D^0) > -160 + 280 \times P_A$, where $P(D^0)$, P_K and P_π are the momenta of the D and the daughter kaon and pion respectively. To avoid large acceptance corrections due to the presence of a trigger counter downstream of the silicon detector, we impose a fiducial cut on the location of the primary vertex. Figure 1 shows the invariant mass distribution for D^*-tagged, right-sign decays $D^0 \rightarrow K^-\pi^+$ and $\overline{D}^0 \rightarrow K^+\pi^-$. A fit to the mass distribution is carried out where a Gaussian function for the signal and a second-order polynomial for the background is used. The fit yields $17\,227 \pm 144$ D^0 and $18\,463 \pm 151$ $\overline{D}^0$ signal events.

The proper time decay distribution is distorted by imposing a detachment cut between the primary and secondary vertices. The reduced proper time, defined as $t' = (\ell - N\sigma_\ell)/(\beta\gamma c)$ where ℓ is the distance between the primary and secondary vertex, σ_ℓ is the resolution on ℓ, and N is the minimum detachment cut applied, removes this distortion. We chose N=5 such that signal to background ratio was maximal. A simulation study was done measuring the differences in measured values of A_{CPT} and ξ using t' in place of t in Equation 5 and Equation 4. The differences were found to be negligible compared to other systematic uncertainties. We plot the difference in right-sign events between $\overline{D}^0$ and D^0 in bins of reduced proper time t'. The background subtracted yields of right-sign D^0 and $\overline{D}^0$ were extracted by properly weighting the signal region $(-2\sigma, +2\sigma)$, the low mass sideband $(-7\sigma, -3\sigma)$ and high mass sideband $(+3\sigma, +7\sigma)$, where σ is the width of the Gaussian. For each
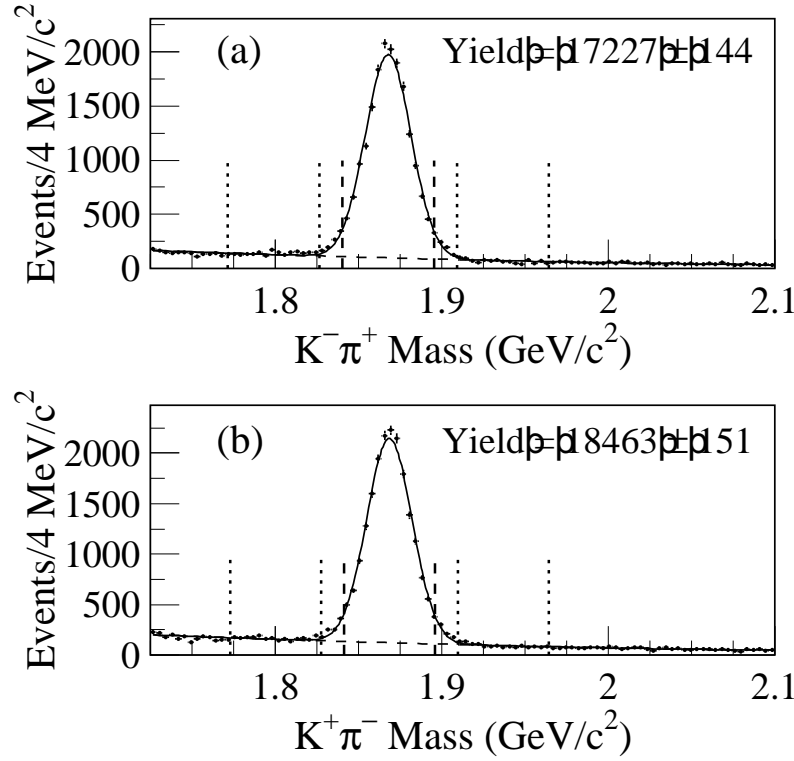
Fig. 1. Invariant mass of ($D^0 \rightarrow K^-\pi^+$ (a); $\overline{D}^0 \rightarrow K^+\pi^-$ (b)) for data (points) fitted with a Gaussian signal and quadratic background (solid line). The vertical dashed lines indicate the signal region, the vertical dotted lines indicate the sideband region.

data point, these yields were used in forming the ratio:

$$A_{\mathrm{CPT}}(t') = \frac{\overline{Y}(t') - Y(t')\frac{\overline{f}(t')}{f(t')}}{\overline{Y}(t') + Y(t')\frac{\overline{f}(t')}{f(t')}}, \tag{5}$$

where $\overline{Y}(t')$ and $Y(t')$ are the yields for $\overline{D}^0$ and D^0 and $\overline{f}(t')$, $f(t')$ are their respective correction functions. The functions $\overline{f}(t')$ and $f(t')$ account for geometrical acceptance, detector and reconstruction efficiencies, and absorption of parent and daughter particles in the nuclear matter of the target. The correction functions are determined using a detailed Monte Carlo (MC) simulation using PYTHIA [18]. The fragmentation is done using the Bowler modified Lund string model. PYTHIA was tuned using many production parameters to match various data production variables such as charm momentum and primary multiplicity. The shapes of the $f(t')$ and $\overline{f}(t')$ functions are obtained by dividing the reconstructed MC t' distribution by a pure exponential with the MC generated lifetime. The ratio of the correction functions, shown in Figure 2(a), enters explicitly in Equation 5 and its effects on the asymmetry are less than 1.3% compared to when no corrections are applied. The FOCUS data contains more $\overline{D}^0$ than D^0 decays due to production asymmetry [19]. The effect on the A_{CPT} distribution is to add a constant offset, which is accounted

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for in the fit.

3 Fitting for the Assymmetry

The A_{CPT} data in Figure 2(b) are fit to a line using the form of Equation 4 plus a constant offset. The value of Γ used in the fit is $\Gamma = 1.6 \times 10^{-12}$ GeV. The result of the fit is $\text{Re}\,\xi\,y - \text{Im}\,\xi\,x = 0.0083 \pm 0.0065$.
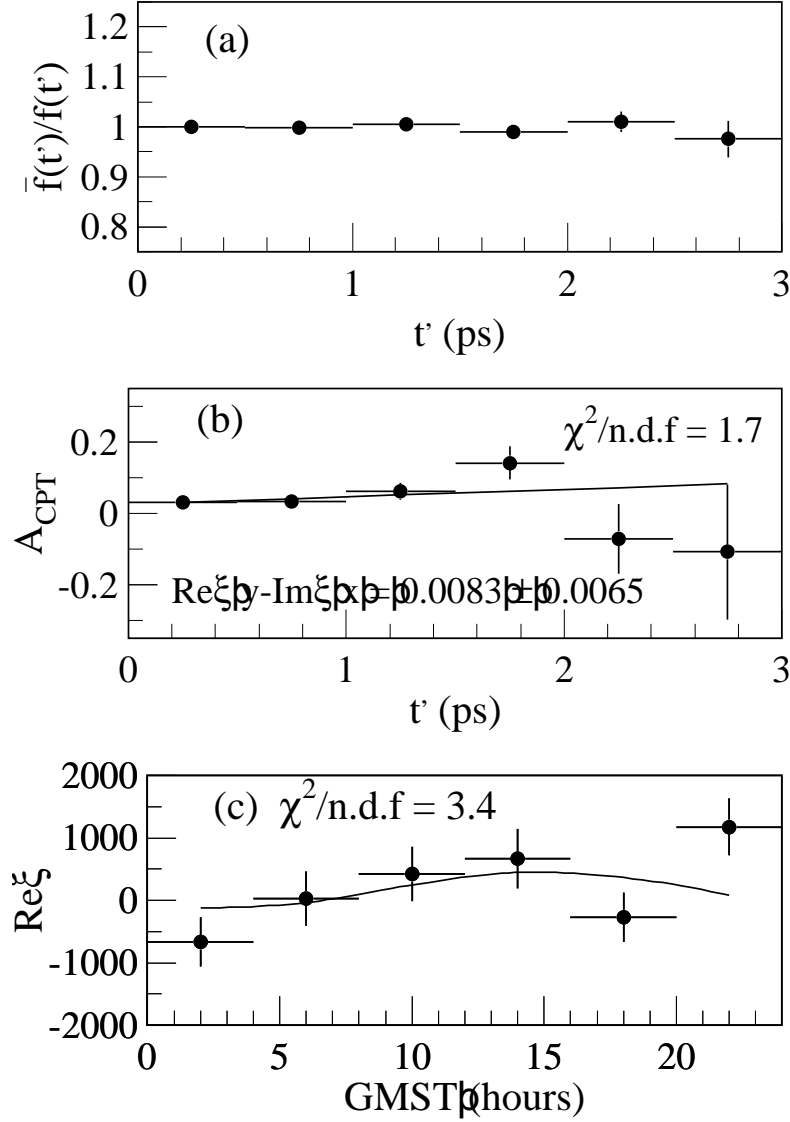

Fig. 2. (a) The ratio of the corrections; (b) A_{CPT} as a function of reduced proper time. The data points represent the A_{CPT} as given in Equation 5 and the solid line represent the fit given in functional form by Equation 4; (c) $\text{Re}\,\xi$ as a function of Greenwich Mean Sidereal Time (GMST).

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4   Lorentz Violation

Any CPT and Lorentz violation within the Standard Model is described by the Standard Model Extension (SME) proposed by Kostelecký at al. [20]. In quantum field theory, the CPT violating parameter ξ must generically depend on lab momentum, spatial orientation, and sidereal time [21,3]. The SME can be used to show that Lorentz violation in the D system is controlled by the four vector Δa_μ. The precession of the experiment with the earth relative to the spatial vector $\vec{\Delta a}$ modulates the signal for CPT violation, thus making it possible to separate the components of Δa_μ. The coefficients for Lorentz violation depend on the flavor of the valence quark states and are model independent. In the case of FOCUS, where D^0 mesons in the lab frame are highly collimated in the forward direction and under the assumption that D^0 mesons are uncorrelated, the ξ parameter assumes the following form [3]:

$$
\begin{aligned}
\xi(\hat{t}, p) = \frac{\gamma(p)}{\Delta\lambda} [\Delta a_0 + \beta \Delta a_Z \cos\chi \\
+ \beta\sin\chi(\Delta a_Y \sin\Omega\hat{t} + \Delta a_X \cos\Omega\hat{t})].
\end{aligned}
\tag{6}
$$

Ω and $\hat{t}$ are the sidereal frequency and time respectively, X, Y, Z are non-rotating coordinates with Z aligned along the Earth's rotation axis, $\Delta\lambda = \Gamma(x - iy)$, and $\gamma(p) = \sqrt{1 + P_{D^0}^2/m_{D^0}^2}$. Binning in sidereal time $\hat{t}$ is very useful because it provides sensitivity to components Δa_X and Δa_Y. Since Equation 15 of Reference [3] translates into $\mathrm{Re}\,\xi\, y - \mathrm{Im}\,\xi\, x = 0$, setting limits on the coefficients of Lorentz violation requires expanding the asymmetry in Equation 3 to higher (non-vanishing) terms. In addition, the interference term of right-sign decays with the doubly Cabibbo suppressed (DCS) decays must also be included since it gives a comparable contribution. One can follow the procedure given by equations [16] to [20] of Reference [3] where the basic transition amplitudes $< f|T|\overline{P^0} >$ and $< \overline{f}|T|P^0 >$ are not zero but are DCS amplitudes. After Taylor expansion the asymmetry can be written as:

$$
\begin{aligned}
A_{\mathrm{CPT}} = \frac{\mathrm{Re}\,\xi(x^2 + y^2)(t/\tau)^2}{2x} \\
\left[\frac{xy}{3}(t/\tau) + \sqrt{R_{\mathrm{DCS}}}\,(x\,\cos\delta + y\,\sin\delta) \right],
\end{aligned}
\tag{7}
$$

where R_{DCS} is the branching ratio of DCS relative to right-sign decays and δ is the strong phase between the DCS and right-sign amplitudes.

5 Fitting for LV Parameters

We searched for a sidereal time dependence [1] by dividing our data sample into four-hour bins in Greenwich Mean Sidereal Time (GMST) [22], where for each bin we repeated our fit in t' using the asymmetry given by Equation 7 and extracted $\mathrm{Re}\,\xi$. The value of $\sqrt{R_{\mathrm{DCS}}}$ used in the fit is taken from Reference [17] and it is 0.06. The resulting distribution, shown in Figure 2(c), was fit using Equation 6 and the results for the expressions involving coefficients of Lorentz violation in the SME were $C_{0Z} \equiv N(x,y,\delta)(\Delta a_0 + 0.6\,\Delta a_Z) = (1.0 \pm 1.1) \times 10^{-16}$ GeV, $C_X \equiv N(x,y,\delta)\Delta a_X = (-1.6 \pm 2.0) \times 10^{-16}$ GeV, and $C_Y \equiv N(x,y,\delta)\Delta a_Y = (-1.6 \pm 2.0) \times 10^{-16}$ GeV, where $N(x,y,\delta) = [xy/3 + 0.06\,(x\cos\delta + y\sin\delta)]$ is the factor which carries the x, y and δ dependence. The angle between the FOCUS spectrometer axis and the Earth's rotation axis is approximately $\chi = 53° (\cos\chi = 0.6)$. We average over all D^0 momentum so $\langle\gamma(p)\rangle \approx \gamma(\langle p\rangle) = 39$ and $\beta = 1$. We also touched base with the previous measurements for the kaon r_K and B meson r_B by constructing a similar quantity r_D [6], $r_D = |\Delta\Lambda|/m_{D^0} = \beta^\mu \Delta a_\mu / m_{D^0} = |\overline{\xi}||\Delta\lambda| = \gamma(p)|\Delta a_0 + 0.6\,\Delta a_Z|/m_{D^0}$. The result for $N(x,y,\delta)\,r_D$ is: $N(x,y,\delta)\,r_D = (2.3 \pm 2.3) \times 10^{-16}$ GeV. Although it may seem natural to report r_D, the parameter r_D (and r_K, r_B) has a serious defect: in quantum field theory, its value changes with the experiment. This is because it is a combination of the parameters Δa_μ with coefficients controlled by the D^0 meson energy and direction of motion. The sensitivity would have been best if $\chi = 90°$.

6 Systematic Errors

Previous analyses have shown that MC absorption corrections are very small [11]. The interactions of pions and kaons with matter have been measured but no equivalent data exists for charm particles. To check any systematic effects associated with the fact that the charm particle cross section is unmeasured, we examined several variations of D^0 and $\overline{D}^0$ cross sections. The standard deviation of these variations returns systematic uncertainties of ± 0.0017, $\pm 0.3 \times 10^{-16}$ GeV, $\pm 0.0 \times 10^{-16}$ GeV, and $\pm 0.1 \times 10^{-16}$ GeV to our measurements of $\mathrm{Re}\,\xi\, y - \mathrm{Im}\,\xi\, x$, C_{0Z}, C_X, and C_Y respectively.

In a manner similar to the S-factor method used by the Particle Data group PDG [17] we made eight statistically independent samples of our data in order to look for systematic effects. We split the data in four momentum ranges and two years. The split in year was done to look for effects associated with target geometry and reconstruction due to the addition of four silicon planes near the

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[1] Sidereal time is a time measure of the rotation of the Earth with respect to the stars, rather than the Sun. Sidereal day is shorter than the normal solar day by about 4 minutes.

targets in January, 1997 [23]. We found no contribution to our measurements of $\mathrm{Re}\,\xi\,y - \mathrm{Im}\,\xi\,x$ and C_{0Z}. The contributions for C_X and C_Y were $\pm 1.3 \times 10^{-16}$ GeV and $\pm 1.6 \times 10^{-16}$ GeV respectively.

We also varied the bin widths and the position of the sidebands to assess the validity of the background subtraction method and the stability of the fits. The standard deviation of these variations returns systematic uncertainties of ± 0.0012, $\pm 0.3 \times 10^{-16}$ GeV, $\pm 0.9 \times 10^{-16}$ GeV, and $\pm 0.5 \times 10^{-16}$ GeV to our measurements of $\mathrm{Re}\,\xi\,y - \mathrm{Im}\,\xi\,x$, C_{0Z}, C_X, and C_Y respectively.

Finally, to uncover any unexpected systematic uncertainty, we varied our ℓ/σ_ℓ and $W_\pi - W_K$ requirements and the standard deviation of these variations returns systematic uncertainties of ± 0.0036, $\pm 1.5 \times 10^{-16}$ GeV, $\pm 1.0 \times 10^{-16}$ GeV, and $\pm 1.1 \times 10^{-16}$ GeV to our measurements of $\mathrm{Re}\,\xi\,y - \mathrm{Im}\,\xi\,x$, C_{0Z}, C_X, and C_Y respectively.

Contributions to the systematic uncertainty are summarized in Table 1 and Table 2. Taking contributions to be uncorrelated we obtain a total systematic uncertainty of ± 0.0041 for $\mathrm{Re}\,\xi\,y - \mathrm{Im}\,\xi\,x$, $\pm 1.6 \times 10^{-16}$ GeV for C_{0Z}, $\pm 1.9 \times 10^{-16}$ GeV for C_X, and $\pm 2.0 \times 10^{-16}$ GeV for C_Y.

Table 1
Contributions to the systematic uncertainty.

Contribution	$\mathrm{Re}\,\xi\,y - \mathrm{Im}\,\xi\,x$	C_X (GeV)
Absorption	± 0.0017	$\pm 0.0 \times 10^{-16}$
Split sample	± 0.0000	$\pm 1.3 \times 10^{-16}$
Fit variant	± 0.0012	$\pm 0.9 \times 10^{-16}$
Cut variant	± 0.0036	$\pm 1.0 \times 10^{-16}$
Total	± 0.0041	$\pm 1.9 \times 10^{-16}$

Table 2
Contributions to the systematic uncertainty.

Contribution	C_{0Z} (GeV)	C_Y (GeV)
Absorption	$\pm 0.3 \times 10^{-16}$	$\pm 0.1 \times 10^{-16}$
Split sample	$\pm 0.0 \times 10^{-16}$	$\pm 1.6 \times 10^{-16}$
Fit variant	$\pm 0.3 \times 10^{-16}$	$\pm 0.5 \times 10^{-16}$
Cut variant	$\pm 1.5 \times 10^{-16}$	$\pm 1.1 \times 10^{-16}$
Total	$\pm 1.6 \times 10^{-16}$	$\pm 2.0 \times 10^{-16}$

7 Summary

We have performed the first search for CPT and Lorentz violation in neutral charm meson oscillations. We have measured $\operatorname{Re}\xi\,y - \operatorname{Im}\xi\,x = 0.0083 \pm 0.0065 \pm 0.0041$ which lead to a 95% confidence level limit of $-0.0068 < \operatorname{Re}\xi\,y - \operatorname{Im}\xi\,x < 0.0234$. As a specific example, assuming $x = 0$ or $\operatorname{Im}\xi = 0$ and $y = 1\%$, one finds $\operatorname{Re}\xi = 0.83 \pm 0.65 \pm 0.41$ with a 95% confidence level limit of $-0.68 < \operatorname{Re}\xi < 2.34$. Within the Standard Model Extension, we set three independent first limits on the expressions involving coefficients of Lorentz violation of $(-2.8 < N(x,y,\delta)(\Delta a_0 + 0.6\,\Delta a_Z) < 4.8) \times 10^{-16}$ GeV, $(-7.0 < N(x,y,\delta)\Delta a_X < 3.8) \times 10^{-16}$ GeV, and $(-7.0 < N(x,y,\delta)\Delta a_Y < 3.8) \times 10^{-16}$ GeV. As a specific example, assuming $x = 1\%$, $y = 1\%$ and $\delta = 15°$ one finds the 95% limits on the coefficients of Lorentz violation of $(-3.7 < \Delta a_0 + 0.6\,\Delta a_Z < 6.5) \times 10^{-13}$ GeV, $(-9.4 < \Delta a_X < 5.0) \times 10^{-13}$ GeV, and $(-9.3 < \Delta a_Y < 5.1) \times 10^{-13}$ GeV. The measured values are consistent with no CPT or Lorentz invariance violation.

8 Acknowlegments

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